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CHARGE CONTROL EXPERIMENTS ON A CH-53E HELICOPTER IN A DUSTY ENVIRONMENT

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ABSTRACT

Charge control tests were carried out on a ground-based, Marine Corps CH-53E helicopter at Davis-Monthan Air Force Base in Tucson, Arizona, during the week of March 19, 1990, to determine if control of the electric fields acting on the engine exhaust gases could be used to reduce the electrification of the helicopter when it operated in a dusty atmosphere.

The test aircraft was flown to a dusty, unpaved area of the base and was then isolated electrically from the earth. When the helicopter engines were operated at ground idle with the rotor locked, the isolated aircraft charged positively, just as had been observed in previous measurements in California. However, when the rotor brake was released in Tucson and the turning rotor created a downdraft that raised dust clouds, the aircraft always became charged more *positively*, to potentials ranging from +30 to +45 kV. (During the earlier tests in clean air in California, operation of the rotor caused the helicopter to charge to negative potentials exceeding −45 kV.)

The dust clouds raised by the rotor downwash in Tucson invariably carried negative space-charges with concentrations of up to -100 nC m^{-3} and caused surface electric fields with strengths of up to 10 kV m^{-1} immediately down wind of the aircraft. The natural charging of the helicopter operating in these dust clouds was successfully opposed by control of the electric fields acting on the hot, electrically-conductive exhaust gases. This control was achieved by placing electrostatic shields around the exhausts from #1 and #3 engines, coupled with the mounting of an isolated electrode inside the shield around #3 exhaust. Control voltages applied to this electrode created the electric fields required to export undesired airframe charges in the exhaust gases.

INTRODUCTION

Aircraft isolated from the earth often acquire electrical charges, which can be dangerous in some situations. For example, when a helicopter hovers near the ground, the charge that it acquires can give severe electrical shocks to ground personnel who come in contact with the aircraft. The cause of helicopter electrification has often been attributed to collisions between the rotor and dust particles in the surrounding air, but significant aircraft electrification has been observed in the absence of dust and other atmospheric particles.

We have been studying this phenomenon for some years and have found that a major cause of helicopter electrification is the flow of electrical currents in the hot, conductive, engine-exhaust gases under the influence of the local electric fields. As a result of these studies, we have been able to control the aircraft electrification by modifying the polarity and strength of the electric fields acting on the hot exhaust gases. The field modification has been accomplished by shielding the engine exhaust gases from the external electric fields with cylindrical wire mesh screens, then applying control voltages of the appropriate polarity to an electrode mounted within one of the shields in a manner that causes the export, on these gases, of the undesired charge residing at some given point on the helicopter.

This technique has been used effectively in experiments to minimize the charges on small helicopters and was successful even when they hovered in clouds of dust where electrification problems have been most severe. It has not been used in flight tests on large helicopters because the present apparatus is experimental and has not yet been engineered to be air-worthy. The current work, however, has been aimed at the development of apparatus that will be suitable for installation on a heavy-lift helicopter.

In some earlier studies at the Marine Corps Air Station in Tustin, California, we found that a ground-based CH-53E helicopter, isolated from the earth, tended to charge positively after the engines were started while the rotor was still stationary. Under low wind conditions, the aircraft sometimes attained potentials, relative to the earth, of about +1.5 kV. Immediately after the rotor brake was released and appreciable downdrafts were caused by the turning rotor, the helicopter potential reversed polarity quickly and voltages in excess of −35 kV were developed relative to the earth. This preference in Tustin for developing negative charge on the aircraft during strong downdrafts could be altered by "export" of negative ions in the exhaust gases when negative control voltages were applied to an electrode immersed in the engine exhaust [1].

Since helicopter electrification reportedly increases when the aircraft operates in a dusty atmosphere, it has been desirable that the charge control technique be tested in an environment with dusty air. Accordingly, arrangements were made with NAVAIR and Marine Corps Squadron HMH 465 for a series of ground-based tests in a dusty area of Davis-Monthan Air Force Base at Tucson, Arizona during March 1990 using a CH-53E helicopter flown in from the Marine Corps Air Station in Tustin, California.

FIELD STUDIES AT TUCSON: MARCH 19–21, 1990

On Monday, March 19, our Marine Corps pilot Captain David Cranford flew the test CH-53E helicopter (tail #YJ21, serial #161996) to an unpaved area on Davis-Monthan AFB in Tucson, Arizona. To isolate the aircraft from the earth, we rolled it up onto three polyethylene slabs, each of which was 1 m^2 and 5 cm thick.

INSTRUMENTATION

The equipment that we used in these studies included:

1. A potential-monitoring voltmeter with "infinite" input impedance patterned after a design by Douglas and Nanewicz [2]. It consists of an electric field mill facing a smooth, metal electrode to which the desired potential is applied. The output for the field mill is a linear function of the applied potential difference between the field mill and the electrode. Potentials (relative to the earth) of up to 80 kV can be measured with this device without any sustained flow of current.

2. Two Faraday cages, each equipped with a sensitive electric field mill, for the direct measurements of space-charges in the exhaust gases and in the atmosphere down wind of the helicopter. The walls of the Faraday cages were made of galvanised steel wire mesh with 1/2-inch openings. The field mill used to sense charge within the cage which was mounted beneath the #3 engine exhaust produced 1.0 V output for a calculated, mean charge concentration of 97 nC m^{-3} while the one mounted in the down-wind Faraday cage required 23 nC m^{-3} for 1.0 V output.

3. Two electric field mills, each mounted in an inverted fashion on a monopod at the height of 1.5 m above the ground for measurement of the atmospheric electric field near the earth's surface.

4. A video camera which was operated at a site about 70 m up wind of the helicopter to provide a record of the dust clouds raised by the rotor downwash.

ELECTROSTATIC SHIELDING AND CONTROL ARRANGEMENTS

The exhaust from #3 engine on the starboard (right) side of the aircraft was shielded electrostatically by an open-ended cylinder, 1 m in diameter and 0.9 m long, constructed from galvanised wire screen with 1/2-inch openings in the mesh. It was isolated both from the airframe and from earth to permit direct measurements of the electrical currents that flowed in the shield during the charge control experiments.

A similar screen cylinder was placed around the exhaust from #1 engine on the port side to shield its exhaust gases from the local electric fields. For comparison, no shielding was used around the exhaust from #2 engine.

A metal electrode was mounted on shielded, porcelain insulators inside the electrostatic shield around the exhaust stack on #3 engine such that the electrode was immersed in the exhaust gases when the engine operated. The electrode was constructed from 5-cm diameter steel tubing bent into a torus that had a diameter of 0.5 m. When high voltages were applied to the electrode, strong electric fields were created between the exhaust stack and the electrode. With this arrangement, ions of one polarity were collected from the emerging exhaust gases while ions having the same polarity as the voltage on the control electrode were exported in a controlled manner from the aircraft.

The voltages applied to the control electrode were supplied by a servo controller which contained two programmable power supplies, one furnishing variable positive high voltages of up to +32 kV, the other delivering up to −32 kV. The output of the supply which was energised at a given time was switched to the control electrode by an internally-selected, high-voltage relay. The servo output voltage was controlled either by the voltmeter that sensed the helicopter potential or manually, by the operator.

OPERATIONS

A total of 7 electrification tests were made on March 20 and 21 with the CH-53E helicopter isolated above the dry, bare earth. During this period, the ground surface was dry with a thin crust of salts where the surface was undisturbed. The ground was initially covered with fine dusty soil on the starboard (#3 engine) side of the aircraft while the port (#1 engine side) polyethylene slabs rested on a patch of weathered, poorly-consolidated asphalt. As dust was blown away by the rotor-induced downdrafts, we provided new dust between several of the runs by scoring and "plowing" the dry earth with tools.

In these studies, engine #3 was always started first and charge-control tests were carried out with this engine operating alone. After they were completed, engine #1 was usually fired up to determine if charge control with #3 engine could be maintained without an electrode inside the shield around #1 exhaust.

The behavior of the charge control system is shown in the data plotted in Figure 1. These were obtained on a cloudless, sunny morning, after #3 engine was started and while the rotor was not turning. The helicopter charged to about +1200 V on its own, presumably as the result of negative ion emission from the exhaust gases under the influence of the fine-weather atmospheric electric field of about −90 V m^{-1} at the earth's surface. At 0916:40 MST, we applied −29 kV to the electrode immersed in the exhaust. This caused the export of negative ions in the exhaust. Immediately afterward, the measurements from the Faraday cage mounted beneath #3 engine showed the presence of an intense, negative space-charge in the exhaust gases. This export of negative charge caused the isolated helicopter to become charged positively; it developed a potential of about +10 kV relative to the earth.

Five seconds later, the electric field at the closer field mill, 30 m down wind, reversed polarity and indicated the presence of negative charge passing overhead. About four seconds later, a similar indication of negative charge aloft began at the field mill at the 47-m distance. The surface wind at this time was about 4 m s^{-1} from the helicopter toward the instruments that were down wind, to the northwest.

At 0917 MST, we reversed the electrode voltage to +25 kV whereupon the sequence was repeated but now with inverted polarity: positive charge was exported, the airframe became charged negatively to about −9 kV, and, shortly afterward, positive space-charge passed over the field mills down wind. When the positive voltage was removed from the electrode, the helicopter was still charged negatively from the just-prior export of positive charge; as a result, negative charge was now exported by the exhaust gases until the aircraft was essentially charge-free, approaching its original condition.

These data illustrate how the charge on the helicopter can be modified by variation of the electric fields acting on the exhaust gases and how the exported charge can be detected down wind of the engines. We now present data from one of the charge control tests at Tucson. The six other tests gave similar results. These tests are described in our report [3] to the Office of Naval Research, copies of which are available from the authors.

CHARGE CONTROL TEST: 1237-1254 MST, MARCH 20, 1990 (WITH RING ELECTRODE 8 CM FROM #3 ENGINE EXHAUST STACK).

The weather conditions: The day was sunny with scattered, high-level alto-stratus clouds, the air temperature was about 27 °C, the relative humidity was estimated to be about 20%, and the surface wind was about 3 m s^{-1} from the southeast.

The results for this test are shown in Figure 2. Engine #3 was started at about 1239 MST and was then operated at ground idle for several minutes. The helicopter was ungrounded at 1240 MST whereupon the aircraft slowly acquired a positive charge. At 1241 MST, we applied −1550 V to the control electrode in the exhaust from #3 engine whereupon the aircraft charged more rapidly with the polarity still positive. The aircraft potential increased, reaching +1500 V at 1241:30 MST when the high voltage supply was turned off. Thereafter, the aircraft potential relaxed back toward zero with a 35-s time-constant.

The rotor began turning in flat pitch at 1242:30 MST and immediately raised a cloud of dust, whereupon the helicopter charged rapidly in the positive polarity and attained a potential of +35 kV within 30 s. This

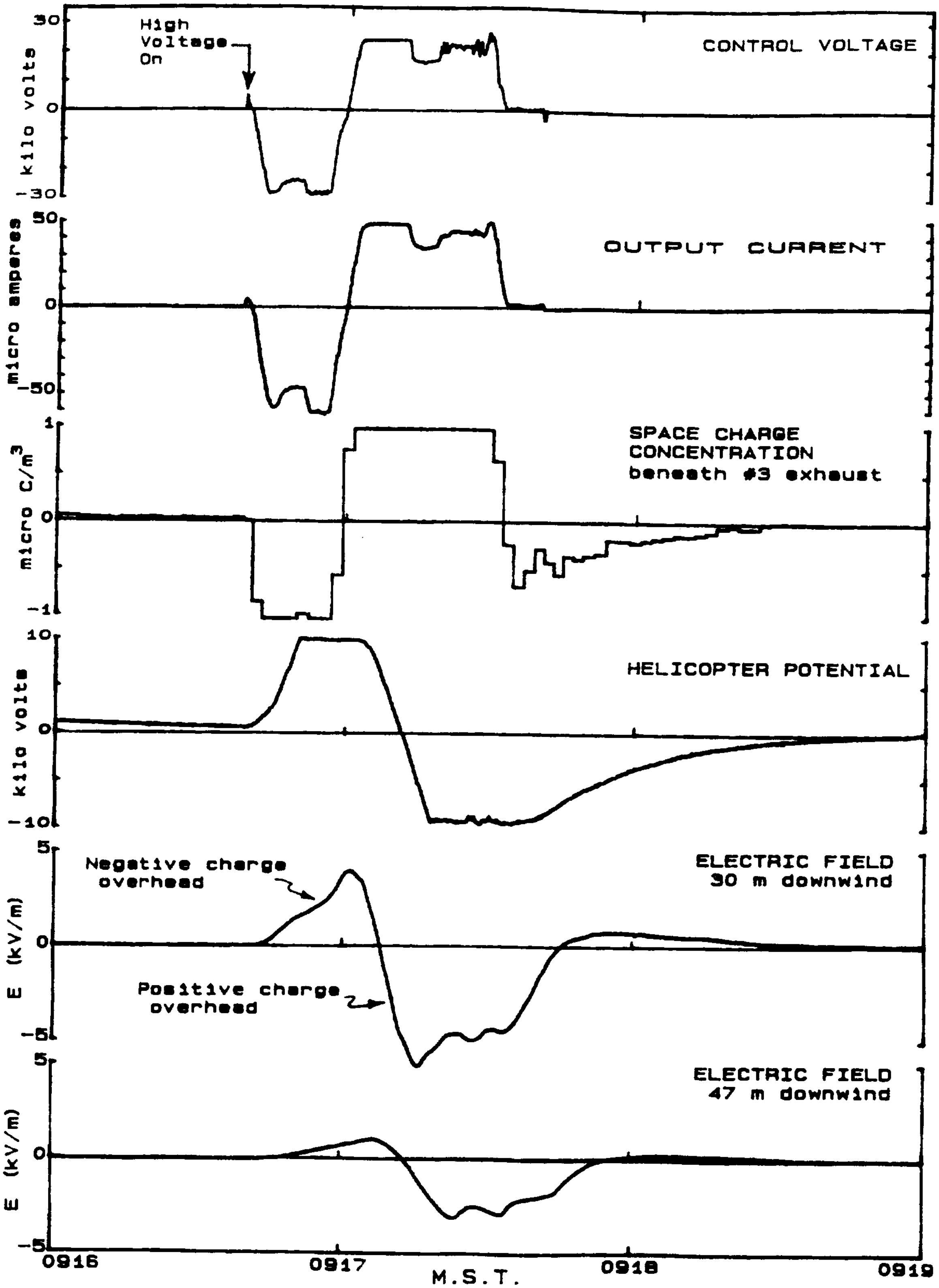

Figure 1: The effects produced by application of high voltages to an electrode immersed in the exhaust from #3 engine while the rotor was stationary (March 21, 1990).

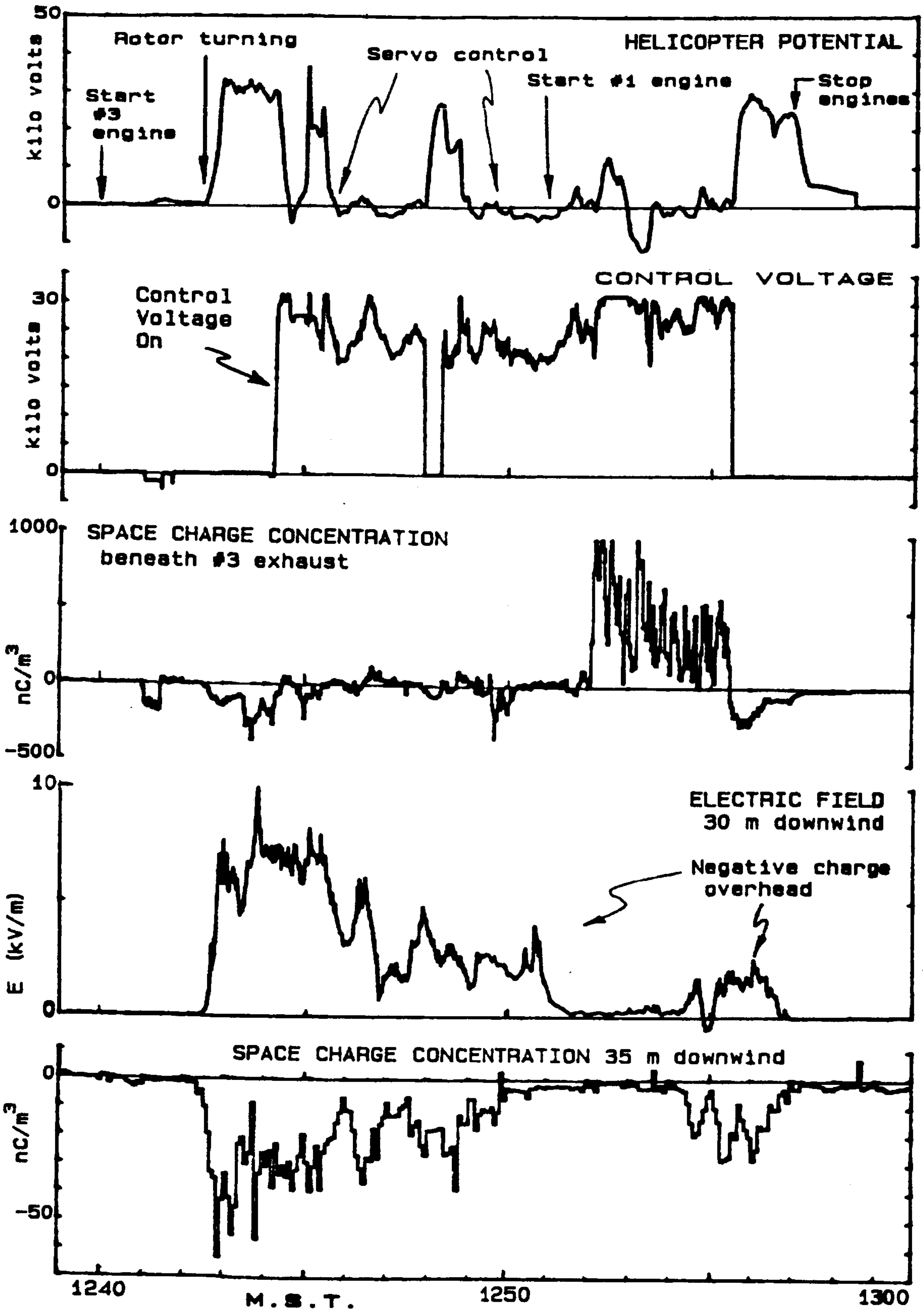

Figure 2: Test of the helicopter charge control system with the ring electrode mounted 8 cm from #3 engine exhaust stack (March 20, 1990).

positive charging in the cloud of dust particles was clearly a result of the rotor motion and did not involve our charge releases since our high voltage system was turned off during this period. Negative space-charges with concentrations of up to -250 nC m^{-3} were measured in the Faraday cage mounted beneath #3 exhaust during this initial, strong charging.

The Faraday cage located 35 m down wind of the rotor hub indicated that the dust clouds away from the aircraft were also negatively charged and carried varying charge concentrations of up to -40 nC m^{-3}. Similarly, the electric field mill 47 m down wind showed field strengths of up to 10 kV m^{-1} with positive polarity, indicating the presence of negative charge overhead.

At 1244:15 MST, we applied +32 kV to the control electrode; this caused positive charge to leave the aircraft and reduced its potential from the +32 kV level. After some adjustments, we were able to maintain the aircraft potential between -2500 V and +1000 V for more than 2 minutes by use of the servo control which varied the voltage on the electrode between +20 and +30 kV and caused the export of a current of about 50 μA in the exhaust. The control was turned off at 1248 MST whereupon the aircraft promptly recharged to +27 kV. We then reactivated the servo control which promptly reduced the helicopter potential to values varying around the sero level where it was maintained by the continued export of positive charges.

None of the positive charge carried away in the exhaust from #3 engine was ever detected by any of the down-wind instrumentation: during all of these tests, the negatively-charged dust clouds raised by the rotor downwash dominated the local atmospheric electricity down wind from the aircraft.

Since we appeared to have some control of the aircraft potential while #3 engine alone was operating, we asked the pilot to start #1 engine with its shielded exhaust. As engine #1 came up to speed, the servo voltage required to minimise aircraft potential increased and the control became less effective with initial excursions in helicopter potential of about 10 kV in both polarities. After the initial oscillation, the servo gained control and maintained the potential to within about 3 kV of sero for the next two minutes. The concentration of positive space-charge measured beneath #3 exhaust became very strong, exceeding +700 nC m^{-3} during this control effort. The servo was turned off at 1255 MST, whereupon the aircraft promptly charged positively again to about +30 kV with the export of up to -200 nC m^{-3} of negative charge recorded in the Faraday cage beneath #3 exhaust.

At 1257 MST, we asked the pilot to stop the engines so that we could change the electrode configuration. While we were able to control the helicopter charge about as expected, a major surprise to us from this test was the anomalous *positive* charging of the helicopter in the presence of the negatively charged dust.

DISCUSSION OF THE HELICOPTER CHARGE CONTROL EXPERIMENTS

The initial, positive charging of the helicopter to about +1 kV after the start of an engine but before the rotor turned (observed both at Tucson and at Tustin) appears to be caused by the fine-weather atmospheric electric field acting on the conductive exhaust gases emitted from the elevated exhaust stack. The strength of the undisturbed atmospheric field that we measured at Tucson was about -100 V m^{-1} and this would have caused negative ions in the exhaust plume to move upward while positive ions would have been driven downward. The effect would have been to cause the airframe to lose negative charge by conduction through the exhaust until it approached the potential of the air at the level reached by the buoyant plume of conductive exhaust gases. The top of the aircraft is at a height of about 7 m. The +1 kV developed by the airframe suggests that the buoyant exhaust gases coupled with the atmospheric potential at a height of about 10 m. This phenomenon provides continuing evidence that charges are transferred from aircraft through the exhaust gases.

A great surprise to us was the strong natural charging of the helicopter with *positive* polarity whenever the rotor caused a downdraft. This polarity of charging is opposite to that previously observed in the clean-air measurements at Tustin. The positive charging of the helicopter at Tucson was associated with the transport of *negative* charges *away* from the aircraft despite the negatively-charged dust cloud that always enveloped it when the rotor turned. One would normally expect that an isolated aircraft surrounded by a cloud of negatively-charged dust would acquire negative charge and become negatively charged itself. Among the processes that could transfer charge between an isolated helicopter and the surrounding air are the following:

1. Ingestion of space-charge in the combustion air drawn into the engine.

   An engine on the CH-53E helicopter operating at 23% capacity as in our tests at Tucson consumes about 400 kg hr^{-1} of hydrocarbon. To burn this fuel stoichiometrically requires about 1.4 $m^3\ s^{-1}$ of air. If the engine air contains the space-charge concentrations of up to -100 nC m^{-3} that we measured in the dust clouds around the helicopter, a charging current of around -0.14 μA would be arriving at the aircraft through each engine. Such currents are of the wrong polarity to charge the helicopter positively and they are too small to be significant in the charging processes encountered during these tests.

2. Collisions between the rotor and dust particles.

   Several different kinds of charge transfer can take place during collisions with dust particles. There can be charge transfers between the rotor blades and negatively-charged particles that leave some of the charges, initially carried by the dust, on the rotor surfaces from which they would be distributed over the entire airframe. Since this would make the aircraft carry a negative net charge, it obviously was not important in our Tucson measurements.

   Charge transfers can also occur during elastic collisions as a result of "contact electrification" which arises from a difference in the "work functions" of the two surfaces in contact. Elastic collisions between the rotor and dust certainly occurred in the tests at Tucson but, in our opinion, they were not the dominant cause of the electrification. One of our reasons for this opinion is that, in tests by Brook *et al.* [4], who caused similar collisions between road dust and an isolated rotor blade turning in the Whirl Tower at the Naval Air Repair Facility in San Diego, the maximum currents observed during intense dust injections were only 0.25 μA and their polarity fluctuated repeatedly during tests with dust of the same apparent composition. One might extrapolate from Brook's measurements to obtain a current of up to 2 μA for the seven rotor blades on the CH-53E helicopter but this is not large enough to explain the currents we encountered.

   Another reason for questioning this explanation is that the CH-53E helicopters used in similar, clean-air charging tests at Tustin charged just as vigorously as did CH-53E YJ21 in the dust in Tucson—but with the opposite, *negative* polarity. There is a common feature however: In Tucson, the atmospheric electric field acting on the helicopter in the negatively-charged dust clouds was upwardly-directed or, in our convention, the surface field under the dust was a "positive" one. In these positive fields, the helicopter always charged *positively* while the rotor was causing a downdraft. On the other hand, at Tustin the atmospheric electric field was always that observed in fine weather which is downwardly-directed and is termed a *negative* one. In such negative fields, all five of the CH-53E helicopters that we tested in Tustin charged *negatively*.

   This coupling between the polarity of the local electric field and that of the charge developed on the helicopter when the rotor creates a downdraft has occurred in all 24 tests that we have made with CH-53E helicopters with ambient electric fields of both polarities. In view of this evidence, it appears that there is a causal relationship involving the ambient electric field which determines the polarity of the helicopter charge.

3. Currents flowing in the exhaust gases.

   In earlier measurements of the electrical conductivity of the CH-53E engine exhaust gases at Tustin, we found that these gases emerge from the exhaust stacks with conductivities of up to 400 pS m^{-1} which indicates that a free charge immersed in such a gas would be essentially neutralised by conduction within 50 ms. After emergence, these gases entrain ambient air quickly. The resulting dilution of the gases and the ion loss by recombination and by attachment to aerosol particles cause the gas conductivities to decrease rapidly with distance from the exhaust stack: we found that the conductivity downstream from engine #1 decreased by e-fold in a distance of about 0.3 m when the rotor caused a downdraft.

   Appreciable electric currents will flow in such conductive gases under the influence of the local electric fields. In quiet air, the effect of such current flows would be to carry charges that act to neutralise the local fields. However, when the rotor causes a downdraft, the charges carried by the cooling exhaust gases can be transported downward and away such that they intensify the field and cause more charges to flow. It appears to us that this occurs regularly with CH-53E operation and results in a positive "feedback" process for charging the aircraft with charging time constants of about 7 s.

CONTROL OF THE CHARGES ON HELICOPTERS

These results clearly show that the residual charge on a helicopter can be reduced and controlled by applying appropriate electric fields to the exhaust gases at a point where they are still electrically conductive and *before* they get involved in the rotor-induced circulation. Despite the predictions and expectations of intense natural charging when the helicopter created a dust cloud, we found no problem in controlling the charging tendencies of a helicopter operating in fairly intense dust.

Our measurements suggest, however, that adequate control will require the use of this technique on the exhausts from all of the engines in operation. The need for this is shown by the experimental results given in Figure 2: During the period from 1246 to 1251 MST, the rotor was driven by #3 engine operating alone. When the servo applied control voltages to the electrode immersed in the #3 engine exhaust gases, it was able to maintain the helicopter potential (and therefore the helicopter charge) at low levels around zero with relatively low emissions of space charges in the exhaust. The application of variable control voltages of about +25 kV apparently was able to counteract the engine's natural tendency to release negative charges under the dusty conditions. (This natural tendency for charge emission when the servo control was not operating is demonstrated in the recordings of negative space charges carried by the exhaust from #3 engine for the times around 1243 MST and, again, after 1255 MST.)

On the other hand, after #1 engine was started around 1251 MST and joined #3 in driving the rotor, servo control voltages of up to +32 kV were required on the #3 exhaust to counteract the charging of the helicopter. Thereafter, high concentrations of positive space charges were detected in the Faraday cage beneath #3 exhaust; these indicate that emissions of high concentrations of positive space charges from #3 engine were needed to offset the releases of negative charges by the shielded, but uncontrolled, #1 engine exhaust. This sequence illustrates the desirability of controlling the electric fields acting on all of the engine exhaust gases if helicopter charges are to be reduced reliably to safe levels.

RECOMMENDATIONS

1. To overcome the natural charging tendencies of an isolated helicopter, we recommend that the exhaust gases be shielded electrostatically from external electric fields and that the fields within the shields be controlled by the application of an appropriate voltage with the same polarity as that of the undesired, residual charge on the aircraft.

2. To optimise this technique, more studies are needed with operating helicopters so that the minimum shielding necessary can be determined.

3. The shields and electrodes should be made airworthy so that the technique can be tested on a heavy-lift helicopter in flight.

4. An operational means of sensing the helicopter's charge or the electric field at some point such as the pendent hook should be investigated. If the servo provides a corrective field to the exhaust which results in making the field at the hook equal to zero, then by definition, the hook is at the potential of its surroundings. If this condition were maintained as a helicopter descended until the hook touched the earth, there would be no spark nor any signigicant charge transfer when contact was made because the hook would have been at ground potential. However, if a ground crewman were to grab the hook when it was hanging 2 m above earth in a dust cloud containing 100 nC of space charge per m^3 of air, the air at that level would be at a potential of about 23 kV relative to the earth and that would be the potential of the helicopter if the field at the hook were zero. A shock to a contacting ground crewman would be inevitable in this case.

   One solution for the avoidance of a shock, suggested by Marx Brook (private communication), would be to use a method similar to the technique for measuring the helicopter potential without drawing a sustained current. A weakly conducting, weighted line or rope could hang down from a potential sensor on the hook so that the line touches the earth or a crewman before he grabs the hook. The virtue of this approach is that it would not require good contact with the earth and is not aimed at direct discharge of the helicopter. Instead, the resulting signal from the sensor on the hook would be used to provide the necessary corrective voltages to the electrode in the exhaust to make the helicopter potential become that of the sensor. With this arrangement, there would be no sparks nor shocks to a ground crewman who contacted any part of the aircraft.

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